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E. H. Markee, Jr., USWB

ABSTRACT

Two graphical multiple-curvilinear regression techniques were used to determine the relationships between an air quality measurement and wind speed, wind direction, temperature and a stability index. Valid relationships of the air quality measurement to wind speed and temperature were found. The net effect of the dispersion parameters predominated over the net effect of the source parameters.

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INTRODUCTION

A two-year joint federal, state, and city-county air quality study was recently completed in the city of Louisville and Jefferson County, Kentucky. An extensive air sampling and meteorological network had been set up for this study. A small sample of the data collected during the course of the study was analyzed to show the relationships of an air quality measurement to meteorological parameters using graphical multiple curvilinear regressions and correlation indices.

The air quality measurement selected for use in this analysis was optical density (soiling index) which is an index of smoke concentrations. Optical density measurements are the logarithm of the ratio of the transmission of light through a clean filter to the transmission of light through a filter on which air-borne particles have collected. These data were available for continuous, consecutive two-hour sampling periods. This relatively short sampling period assisted in maintaining uniformity of the values of the meteorological parameters within the sampling period. Data representing the early morning period of the day (0000 - 0500 CST) were desired to minimize the effect of the diurnal trends of optical density measurements and meteorological parameters. In this analysis, the measurements for one sampling location for the period 0000 to 0200 CST during February, March, and April 1956 were used.

The meteorological parameters used in this analysis were wind speed, wind direction, temperature, and a stability index. The wind speeds, wind directions, and temperatures used were means of the two hourly average values for the sampling period. In the absence of a direct stability measurement, a stability index was calculated from surface temperature measurements. The index is the difference between the mean of the daytime maximum temperatures before and after the sampling period, and the mean temperature during the sampling period, plus the change in maximum temperatures:

$$S.I. = 1/2\ (T_{x_1} + T_{x_2}) - T_m + (T_{x_2} - T_{x_1})$$

where S.I. is the stability index, T_{x_1} is the maximum temperature on the previous day, T_{x_2} is the maximum temperature on the day of the sample, and T_m is the mean temperature during the sampling period. Low values indicate instability and high values, stability. The meteorological measurements, made two miles from the optical density measuring site, are considered representative of the air sampling location.

METHOD OF ANALYSIS

The optical density data were divided into two groups, one group to be used to estimate graphically the regression curves and the other to check the representativeness of the graphical estimates for independent data from the same population. The data were divided by first ranking the optical density measurements and then by placing the odd-numbered rank values into the first group and the even-numbered values into the second group. The optical density data with missing meteorological data for the same time period were then eliminated. Forty-two

cases were used to derive the relationships and thirty-four cases were used for checking purposes.

The regressions and intercorrelations (Table I) among the meteorological parameters, and the regression (Figs. 1-4) and correlation (Table II) of optical density on each meteorological parameter were computed. A graphical curve-fitting method was used to estimate the regression curves. For each pair of parameters, except those which contain wind direction, the regression curves were first approximated by plotting a scatter diagram and graphically calculating and plotting moving median values of one parameter for an interval of the other parameter. Then a smooth curve of best fit was drawn to these moving medians (Figs. 1, 2, & 4). The regression values on wind direction are weighted moving average values (Fig. 3), computed from the individual values for the wind direction under consideration, and the values for one compass point on either side of the direction under consideration. These averages are twice the sum of the values for the direction under consideration plus the sum of the values for the adjacent directions, divided by the sum of twice the number of observations for the direction under consideration and the number of observations for the adjacent directions. All of the correlation indices (ρ) were computed by the following formula:

$$\rho = \sqrt{1 - \frac{(Y-Y_c)^2}{(Y-\bar{Y})^2}}$$

where $(Y-Y_c)$ is the deviation of an individual value from its graphically estimated value as determined from the regression curve, and $(Y-\bar{Y})$

is the deviation of an individual value from the mean of all of the values. Also the percentages of the variance explained were computed by squaring each correlation index. These correlations show the total relationship of each variable to every other variable used in the study.

Two graphical multiple curvilinear regression techniques were used to show the net effect of each meteorological parameter and the total effect of all of the meteorological parameters on optical density. Both techniques considered optical density as the dependent variable and the meteorological parameters as independent variables. In each of the techniques, a regression curve was drawn for the dependent variable on the first independent variable. The relative residuals* were then computed and plotted against the next independent variable. A regression curve of the relative residuals from the first regression curve versus the second independent variable was drawn. This procedure was continued until the net effect of each independent variable was eliminated. The same procedures for the drawing of the regression curves, previously described, were used in both techniques. Cumulative correlation indices and cumulative percents of variance explained were computed after the elimination of the effect of each independent variable so that computation could be made of the net percent of variance explained by each independent variable after elimination of the effect of the preceding independent variables. To compute multiple

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* A relative residual is the ratio of the observed value minus the regression value to the regression value.

correlation indices, the optical density values were estimated from the regression curves and used in one of the following formulas, depending on the number of independent variables eliminated:

$$Y_1^c = Y_1^i$$
$$Y_2^c = Y_1^i \ (100 \div R_1^i)/100,$$
$$Y_3^c = Y_1^i \ (100 \div R_1^i \div R_2^i)/100, \text{ and}$$
$$Y_4^c = Y_1^i \ (100 \div R_1^i \div R_2^i \div R_3^i)/100$$

where Y_1^c, Y_2^c, Y_3^c, and Y_4^c are calculated optical density values after elimination of the first independent variable, the first and second independent variables, the first, second, and third independent variables, and all of the independent variables, respectively; where Y_1^i is regression value from the first regression curve, and R_1^i, R_2^i, and R_3^i are relative regression values from the second, third, and fourth regression curves, respectively. After calculation of the computed optical density values, correlation indices and percents of explained variance were computed by using the previously described formulas. The net variance explained by each independent variable after elimination of the effect of the preceding variables was then computed by subtracting the variance explained by the previous variables from the variance explained, including the variable in question. Also, standard errors of estimate (S_y) were computed for each correlation index by using the following formula (Table IV):

$$S_y = \sqrt{\frac{(Y-Y_c)^2}{N}}$$

The first technique presents two orders of variable elimination, one of which was selected because of its relationship to the statistical method(2) and the other because of its relationship to air quality. Only first approximation regression curves were drawn so that the order of variable elimination would be significant.

The first order eliminates the effect of each independent variable according to its total influence on optical density, as determined by the correlation indices in Table II. The order was wind speed (Fig. 1), stability index, wind direction, and temperature (Figs. 5 and Table III-A-1).

The second order eliminates the effect of each independent variable according to its assumed general relationship to air quality. The meteorological variables related to effective air pollution source strength are temperature and wind direction, and the variables affecting the dispersion of pollutants are wind speed and stability. Because the dispersion variables were eliminated first in the previous order of elimination, the source variables were eliminated first in this order. Therefore, the order was temperature (Fig. 4), wind direction, wind speed, and stability index (Figs. 6 and Table III-A-2).

The second technique used the multiple graphical curvilinear regression method, after Ezekiel(2). This method involves a series of successive approximations which adjust the first approximation regression curves until no further adjustment can be made graphically. The method produces a net regression curve for each independent variable from which the effects of all of the other independent variables have been eliminated. Each curve is independent of order of

elimination. Therefore, this method will show the net variances of optical density explained by each meteorological variable which are independent of order (Figs. 7 and Table III-B).

Checks to determine the representativeness of the regression curves for a set of independent data were made by computing the standard errors of estimate (S_y') after the elimination of each independent variable (Table IV) and the total correlation indices for each technique (Table V) of the second group of data on the sets of regression curves obtained in the two multiple regression techniques.

RESULTS

Wind speed explains considerably more of the variance of optical density, in its total effect, than any of the other meteorological parameters (Table II), and it explains approximately one-half of the variance of optical density in its net effect after elimination of the effect of the other meteorological parameters (Table III-B). All of the regression curves relating wind speed to optical density have the same characteristics (Figs. 1, 6b, & 7a). Since a check of these regression curves with independent data shows that standard errors of estimate decrease when progressing from the preceding step to the step which relates wind speed to optical density (Table IV), the form of relationship shown by the curves is valid.

Stability index ranks second in total influence on optical density (Table II). However, with the removal of wind speed effect, the amount of variance eliminated by stability is reduced considerably (Table III). Unlike the wind speed relationships, the characteristics of the stability index regression curves are not similar in all of the

methods of analysis. In the total and net relationships (Figs. 2 & 7d) the curves are similar, as they are also in the statistical and meteorological orders of elimination (Figs. 5a & 6c). According to the check of these regression curves with the independent data, neither type of curve is representative, because the standard errors of estimate do not decrease when progressing from the preceding step to the step which relates stability index to optical density (Table IV).

Wind direction ranks third in total influence on optical density (Table II), and net effect (Table III-B). After elimination of the effect of the other meteorological parameters, the variance explained by it is reduced. Each regression curve relating wind direction to optical density is fairly consistent with the other corresponding curves showing the same relationship (Figs. 3, 5b, 6a, & 7b) but, according to the independent data regression curve check (Table IV), the regression curves are not representative for the same reason that was described in the previous paragraph on the stability index parameter.

Finally, temperature ranks last in total effect on optical density (Table II) with considerably less net influence. However, all of the regression curves relating temperature to optical density have the same characteristics (Figs. 4, 5c, & 7c) and these curves are representative because of the general decrease of the standard error of estimate when the temperature regression curves are used with the independent data (Table IV).

The total correlation index is highest in the successive approximation technique and lowest in the meteorological order of elimination (Table III). According to the independent data check, the most representative method is the first technique, with the statistical

order of elimination (Table V).

DISCUSSION OF THE RESULTS

It is concluded that wind speed is the most important variable in the determination of optical density at ground level. About one-half of the variance in optical density can be explained by this single parameter. A key feature of this variable is its relative independence of other meteorological variables in its relationship to optical density. The wind speed regression curves also indicate the true relationship between these two variables.

Stability index, although ranking second in total variance reduction of optical density, is very closely related to wind speed in its relation to optical density, so that most of the variance explained by stability can be explained by wind speed alone. The regression curves do not show true net or total relationships between the stability index and optical density, a deficiency indicated by the check of the regression curves with independent data.

Wind direction regression curves also are not representative. These spurious results are caused by data insufficient to produce meaningful results. A much larger sample of homogeneous data which can be classed into sixteen compass points with a significant number of cases in each wind direction is necessary to show the influence of wind direction.

This method of analysis adequately describes the relationship of temperature to optical density because the regression curves are representative. However, there is very little net temperature effect and the temperature curves may represent changes of optical density with

time because of the time period of three months involved in the study. In order to separate the direct and indirect (i.e., time trend) influences of temperature several years of data for the same months would have to be analyzed.

The net effect of the dispersion variables, wind speed and stability index, on optical density is greater than the net effect of the source variables, wind direction and temperature, by a factor of approximately seven. It is concluded that the effective sources of air-borne particles measured by the optical density sampler were rather uniformly distributed about the sampling location.

It can be seen that the statistical order of elimination, using only first approximation regression curves, gives the more representative results of the two techniques presented. It is suspected that the successive approximation method tends to make too great a correction of the regression curves for individual points and not enough for general trends. The statistical order, which eliminates the effect of each independent variable according to its total influence on the dependent (air quality) variable, would, in general, be expected to yield the better results.

EVALUATION OF THE STUDY

This study represents only a small portion of the data restricted to one sampling location, one time of day, one season of the year, and one type of air sampling data. It is believed that valid relationships of wind speed and temperature to these optical density data were found using this method, but the stability index and wind direction relationships are questionable.

This method of analysis, however, does provide a useful first approximation to a refined objective method of determining the amount and character of the relationships of an air quality measurement to measurable meteorological parameters.

ACKNOWLEDGEMENTS

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2. Ezekiel, Mordecai, Methods of Correlation Analysis, 1941, Second Edition, John Wiley and Sons.

3. University of Michigan Institute of Industrial Health, "A.I.S.I. Automatic Smoke Sampler." Encyclopedia of Instrumentation for Industrial Hygiene, 1956, p. 641.

Table I. Intercorrelations among Meteorological Parameters

Pairs of meteorological parameters	Correlation index	Percent of variance explained
Wind speed on wind direction	0.42	17.6
Temperature on wind direction	0.62	38.4
Stability index on wind direction	0.52	27.0
Temperature on wind speed	0.54	29.2
Stability index on wind speed	0.65	42.3
Stability index on temperature	0.53	28.1

Table II. Correlations of Optical Density on:

Meteorological parameters	Correlation index	Percent of variance explained
Wind speed	0.69	47.6
Stability index	0.49	24.0
Wind direction	0.36	13.0
Temperature	0.33	10.9

Table III. Graphical Multiple Curvilinear Correlations

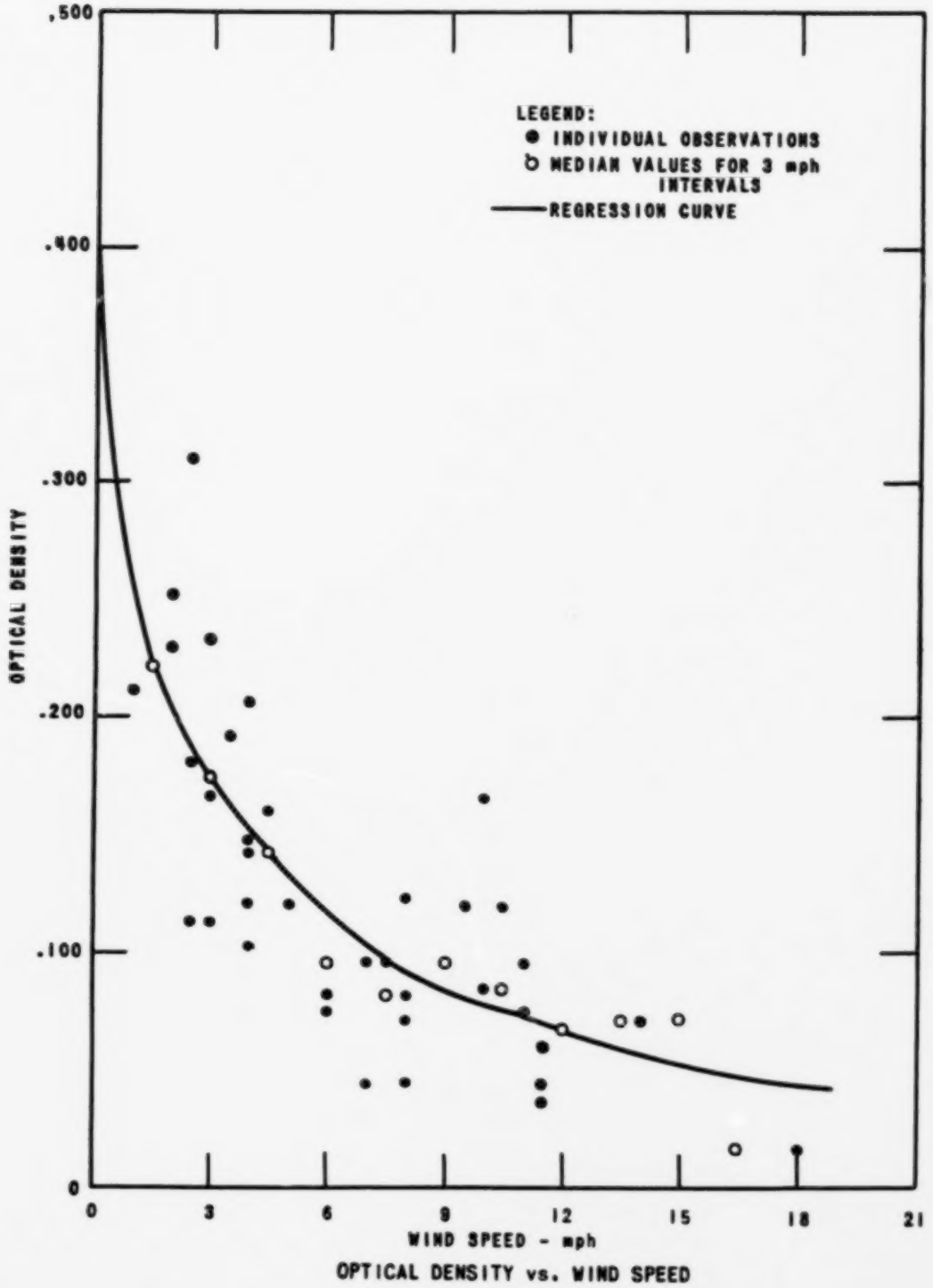
Techniques	Cumulative correlation index	Cumulative percent of variance explained	Percent of variance explained
A. Orders of elimination technique (1st approximations)			
1. Statistical order of elimination			
Wind speed	0.69	47.6	47.6
Stability index	0.73	53.3	5.7
Wind direction	0.79	62.4	9.1
Temperature	0.80	64.0	1.6
2. Meteorological order of elimination			
Temperature	0.33	10.9	10.9
Wind direction	0.58	33.6	22.7
Wind speed	0.67	44.9	11.3
Stability index	0.69	47.6	2.7
B. Successive approximation technique			
Wind speed	0.73	53.3	53.3
Wind direction	0.78	60.8	7.5
Temperature	0.79	62.4	1.6
Stability index	0.84	70.6	8.2

Table IV. Standard Errors of Estimate

Techniques	S_y	S'_y
A. Orders of elimination technique		
1. Statistical order of elimination		
Wind speed	±.060	±.061
Stability index	±.056	±.062
Wind direction	±.050	±.065
Temperature	±.049	±.056
2. Meteorological order of elimination		
Temperature	±.077	±.072
Wind direction	±.067	±.075
Wind speed	±.061	±.065
Stability index	±.059	±.066
B. Successive approximation technique		
Wind speed	±.056	±.063
Wind direction	±.052	±.068
Temperature	±.051	±.068
Stability index	±.044	±.068

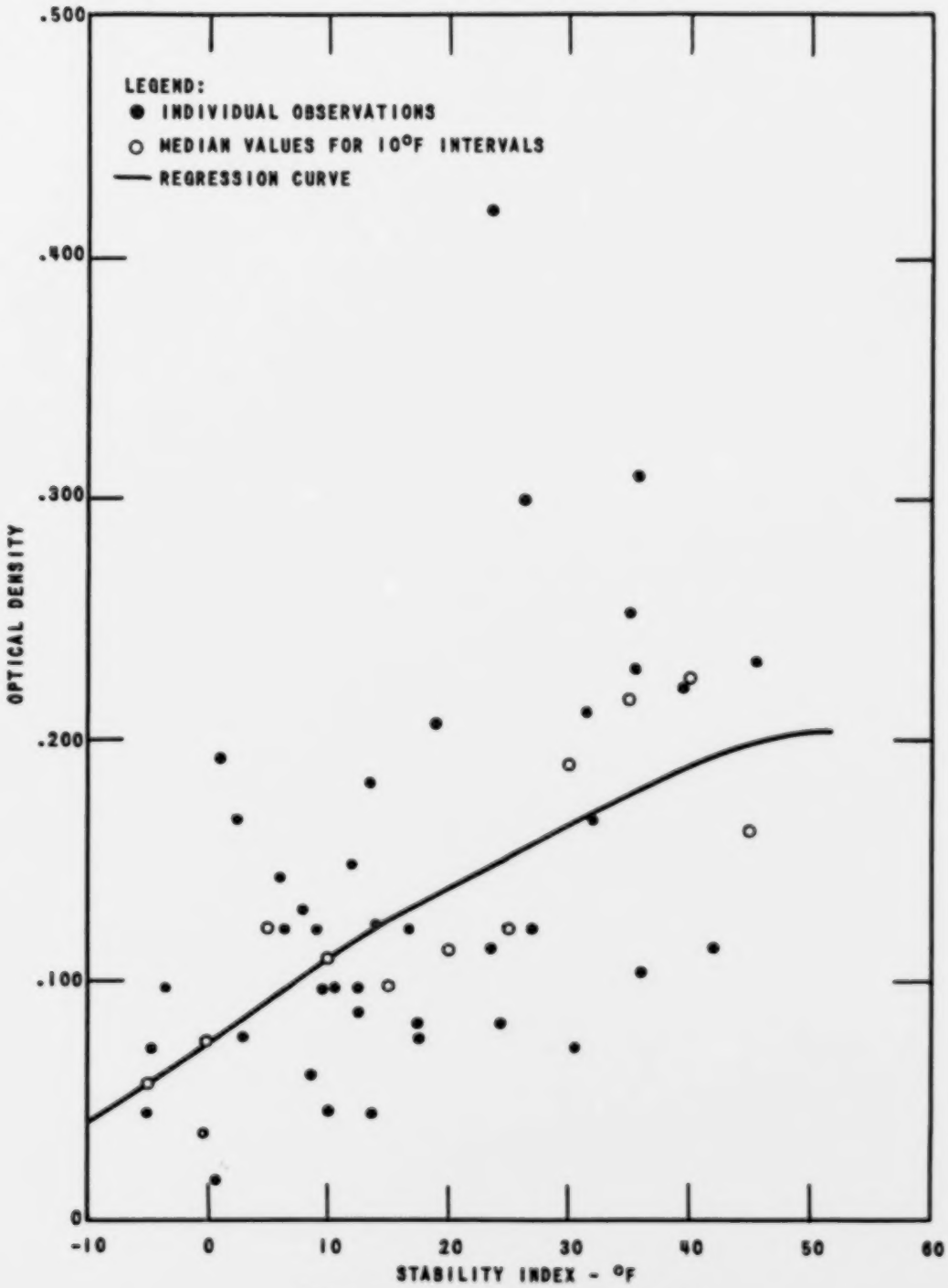
Table V. Checks using Independent Data

Techniques	Correlation index	Percent of variance explained
A. Orders of elimination technique		
1. Statistical Order of elimination	0.63	39.7
2. Meteorological order of elimination	0.41	16.8
B. Successive approximation technique	0.35	12.3



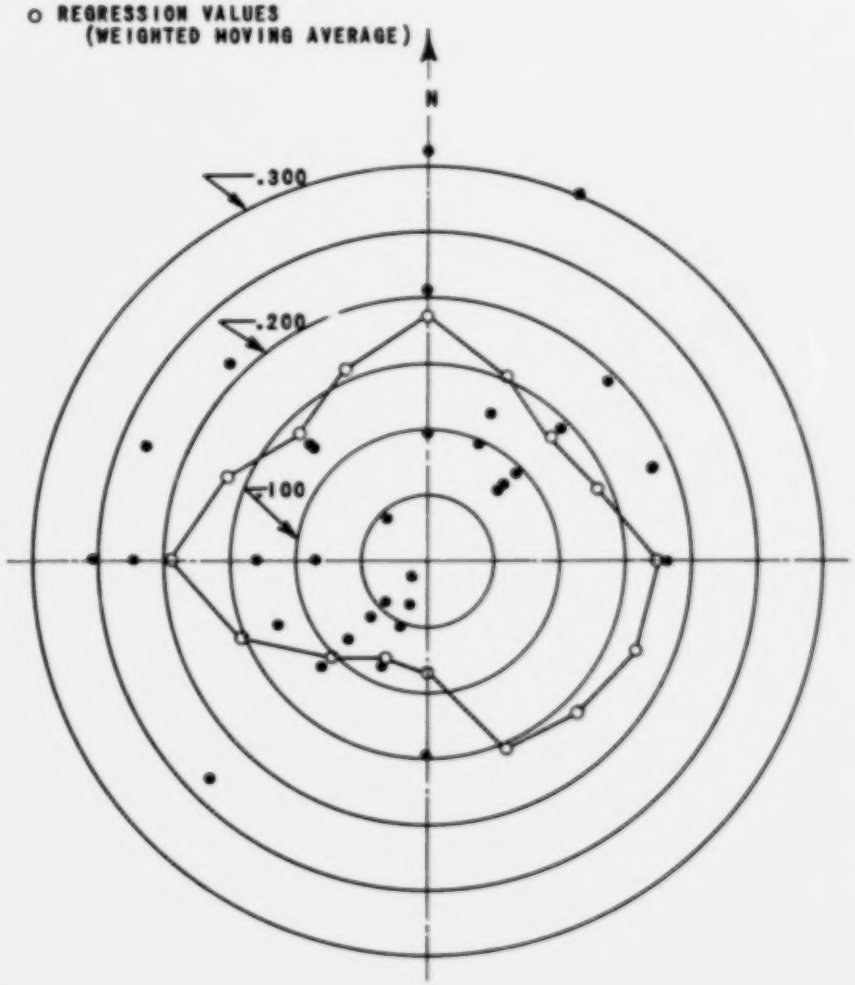
OPTICAL DENSITY vs. WIND SPEED

Figure 1



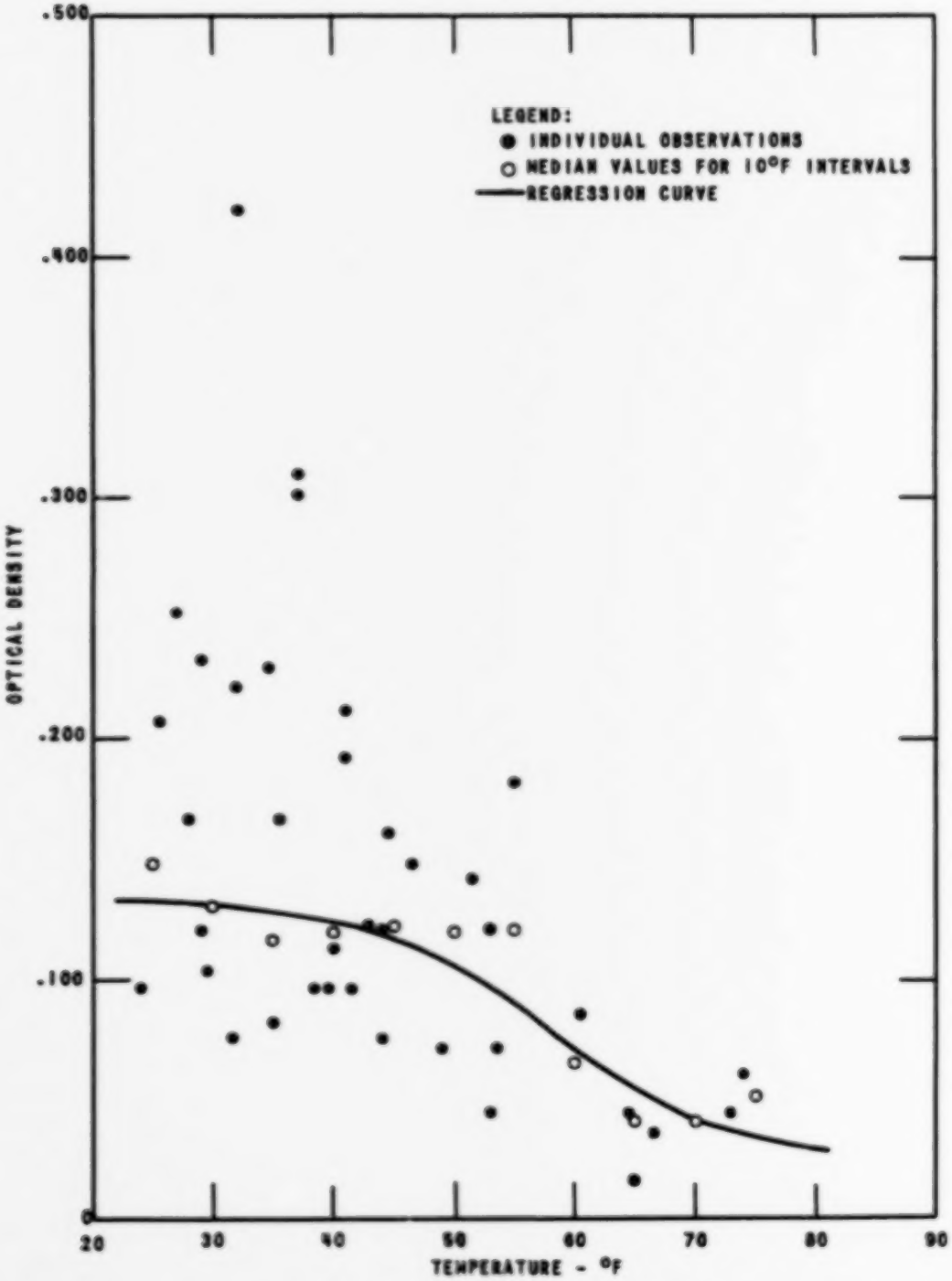
OPTICAL DENSITY vs. STABILITY INDEX

Figure 2



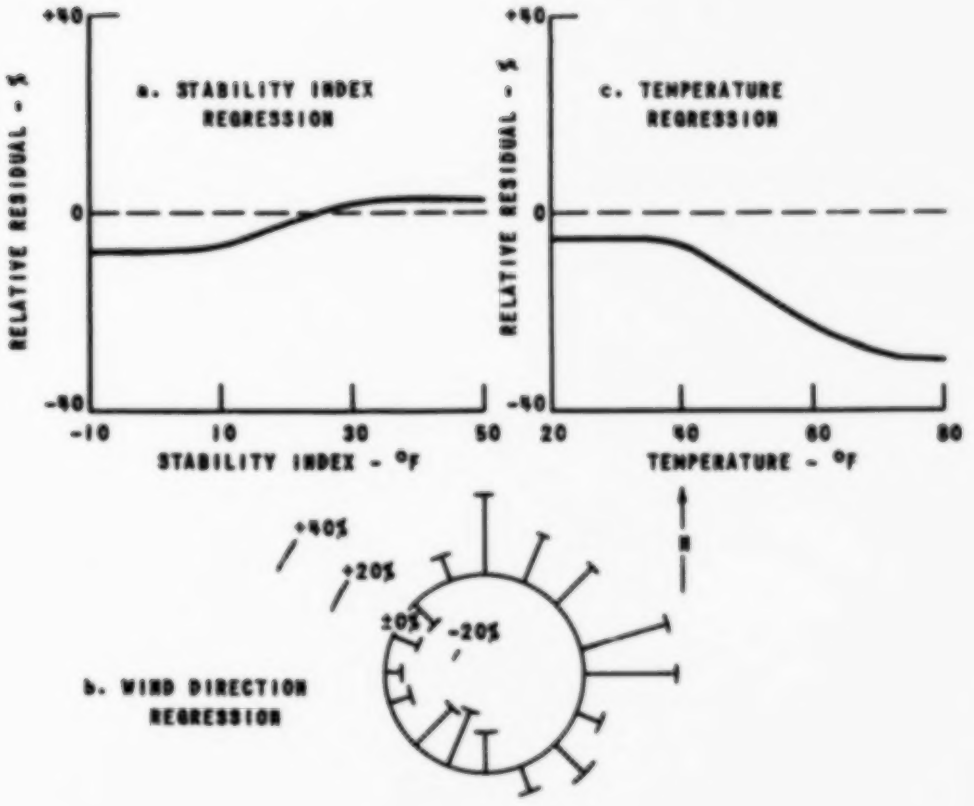
OPTICAL DENSITY VS. WIND DIRECTION

Figure 3



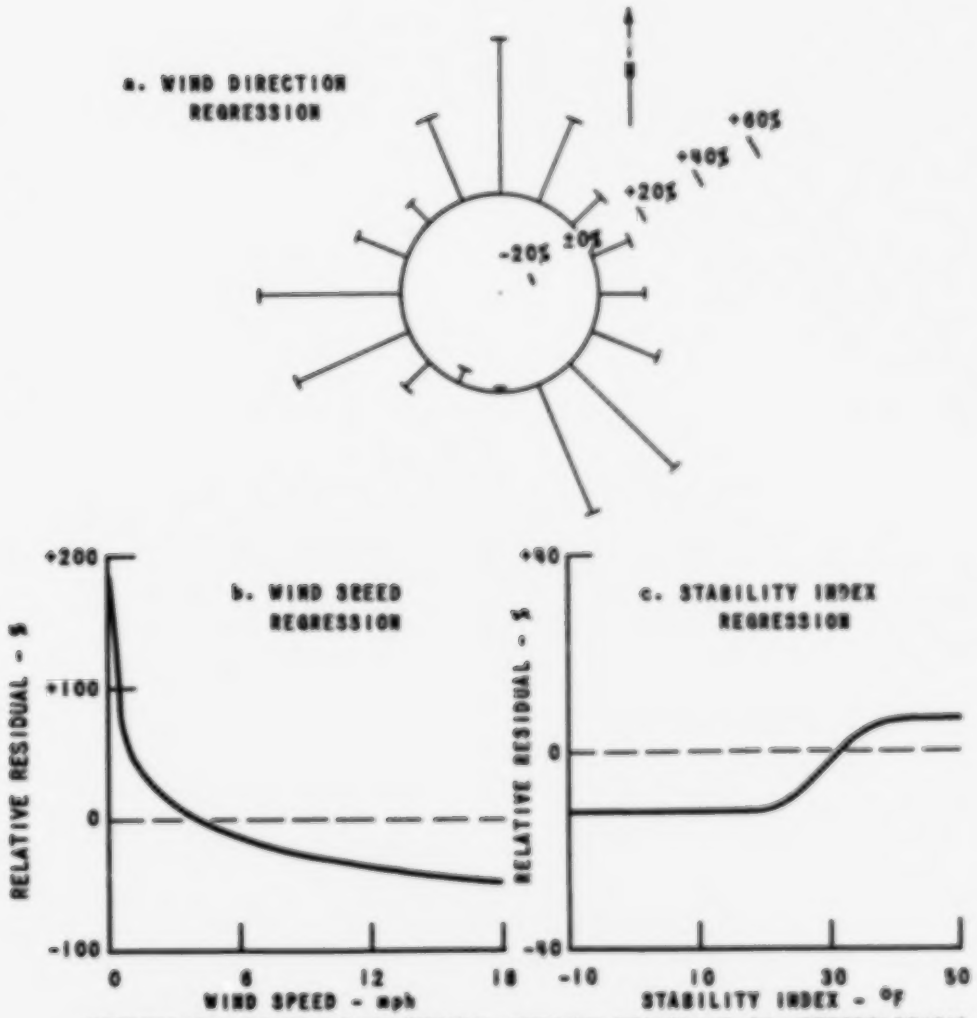
OPTICAL DENSITY vs. TEMPERATURE

Figure 4



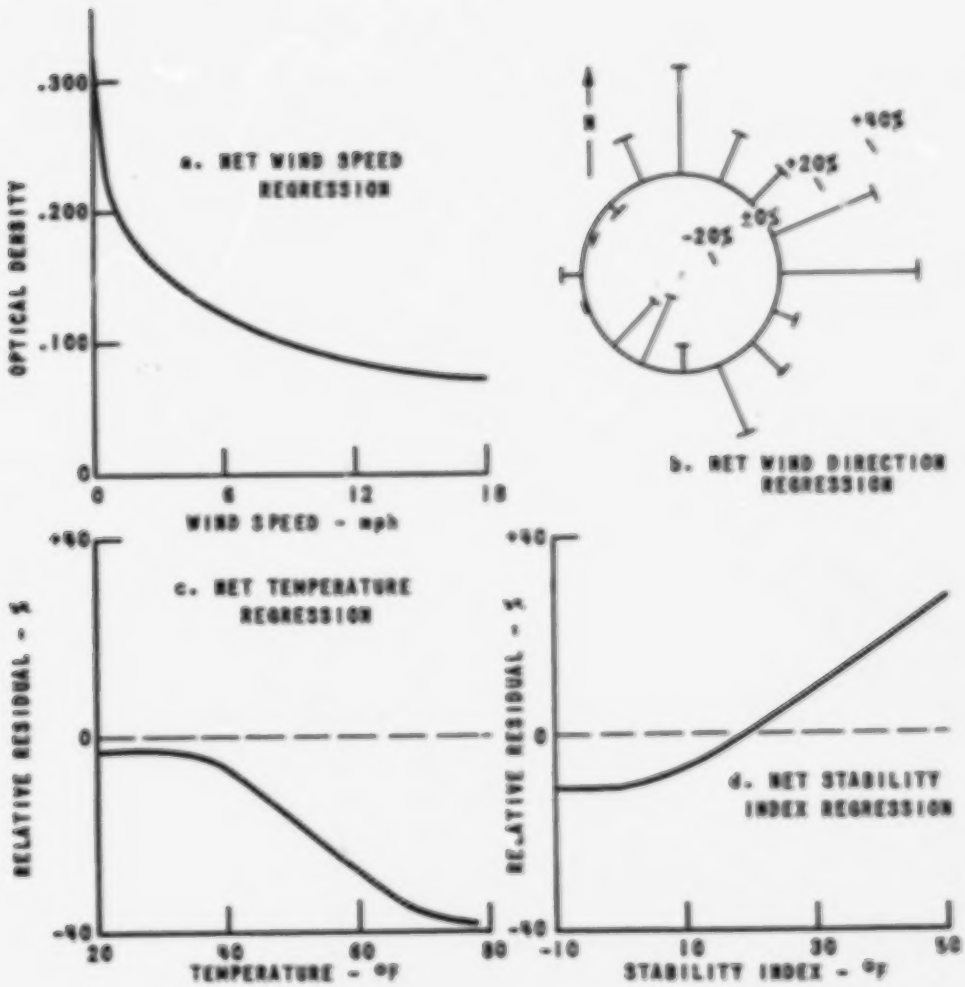
REGRESSIONS OF RELATIVE OPTICAL DENSITY RESIDUALS ON METEOROLOGICAL PARAMETERS - STATISTICAL ORDER OF ELIMINATION (SEE TEXT).

Figure 5



REGRESSIONS OF RELATIVE OPTICAL DENSITY RESIDUALS ON METEOROLOGICAL PARAMETERS - METEOROLOGICAL ORDER OF ELIMINATION (SEE TEXT).

Figure 8



NET REGRESSIONS OF OPTICAL DENSITY ON METEOROLOGICAL PARAMETERS - SUCCESSIVE APPROXIMATION TECHNIQUE (SEE TEXT).

Figure 7